SAE TECHNICAL PAPER SERIES

00ICES-234

International Space Station Carbon Dioxide Removal Assembly Testing

James C. Knox
NASA Marshall Space Flight Center

The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

30th International Conference on Environmental Systems
Toulouse, France
July 10-13, 2000

400 Commonwealth Drive, Warrendale, PA 15096-0001 U. S. A. Tel: (724) 776-4841 Fax: (724) 776-5760

ISSN 0148-7191

Printed in USA

00ICES-234

International Space Station Carbon Dioxide Removal Assembly Testing

James C. Knox
NASA Marshall Space Flight Center

ABSTRACT

Performance testing of the International Space Station Carbon Dioxide Removal Assembly flight hardware in the United States Laboratory during 1999 is described. The CDRA exceeded carbon dioxide performance specifications and operated flawlessly. Data from this test is presented.

INTRODUCTION

This paper reports the Carbon Dioxide Removal Assembly (CDRA) and Atmosphere Revitalization System (ARS) testing performed at Kennedy Space Center in support of the International Space Station program. The specific test discussed is the Closed Hatch Environmental Control and Life Support System (ECLSS) Qualification test. The test article is the US Laboratory (USL), to be launched on assembly flight 5A. Closed Hatch ECLSS (CHE) Qualification testing was conducted in April and May of 1999.

The CDRA is described first, as the primary subject of this paper. The overall Atmosphere Revitalization Subsystem will be described with respect to functionality, connectivity, and interfaces with other subsystems.

The test configuration of the US Lab as it relates to the ARS operation will be described. Support equipment used during the CHE Qualification Test will be identified. The test objectives and operational steps will be outlined. Finally, test data pertaining to ARS operations will be presented and conclusions drawn.

CDRA DESCRIPTION

As show in Figure 1, the CDRA is tightly integrated and mounted on slides for installation in the Atmosphere Revitalization System rack. Air selector valves are visibly numbered 101 through 106. The blower and precooler orbital replacement unit (ORU) is visible in the right center section of the drawing. Process air and coolant water interfaces are on the lower right of the drawing. The sorbent beds are not clearly visible, but are behind the valves and tubing. Controllers for the bed heaters, air-save pump, and blower are on the left side, identified by the many electrical connectors. The air-save pump resides below the controllers.

The operation of the CDRA can be explained with the aid of the schematic shown in Figure 2. The CDRA continuously removes carbon dioxide (CO_2) from the ISS atmosphere. The four beds consist of two desiccant beds and two CO_2 sorbent beds. The system operates such that one desiccant bed and one CO_2 sorbent bed are adsorbing while the other two beds are desorbing. When a new half cycle begins, the beds switch sorbent modes. The incoming air stream to the CDRA is downstream of a condensing heat exchanger, and has a dewpoint and drybulb temperature of 4.4 to 10°C (40 to 50 °F) [1]. The air stream passes first through a desiccant bed to remove much of the moisture from the process air. The temperature of the air stream rises as it flows through the desiccant bed due to the heat of adsorption. The process air is then drawn through the system blower and then through an air-liquid heat exchanger or precooler. The precooler increases CO_2 sorbent efficiency by reducing process air temperature before entering the CO_2 sorbent bed. Prior to returning to the cabin, the air stream passes through the desiccant bed that adsorbed moisture from the previous half cycle. The wet desiccant bed desorbs this moisture to the air stream and returns it to the cabin atmosphere. This is called a water-save system, in contrast to the 2-bed Skylab system, which vented adsorbed water to space.

The alternate CO_2 sorbent bed desorbs by heating with integral electrical heaters and application of space vacuum or, for ground testing, a simulated space vacuum. The heat supplied by the electrical heaters serve two purposes; it breaks the bond the CO_2 has with the sorbent material, and in the subsequent half-cycle heats the passing air-stream to dry out the desorbing desiccant bed. For the first 15 minutes of each half-cycle, the air-save pump operates to remove residual air from the desorbing sorbent bed and returns it to the cabin.

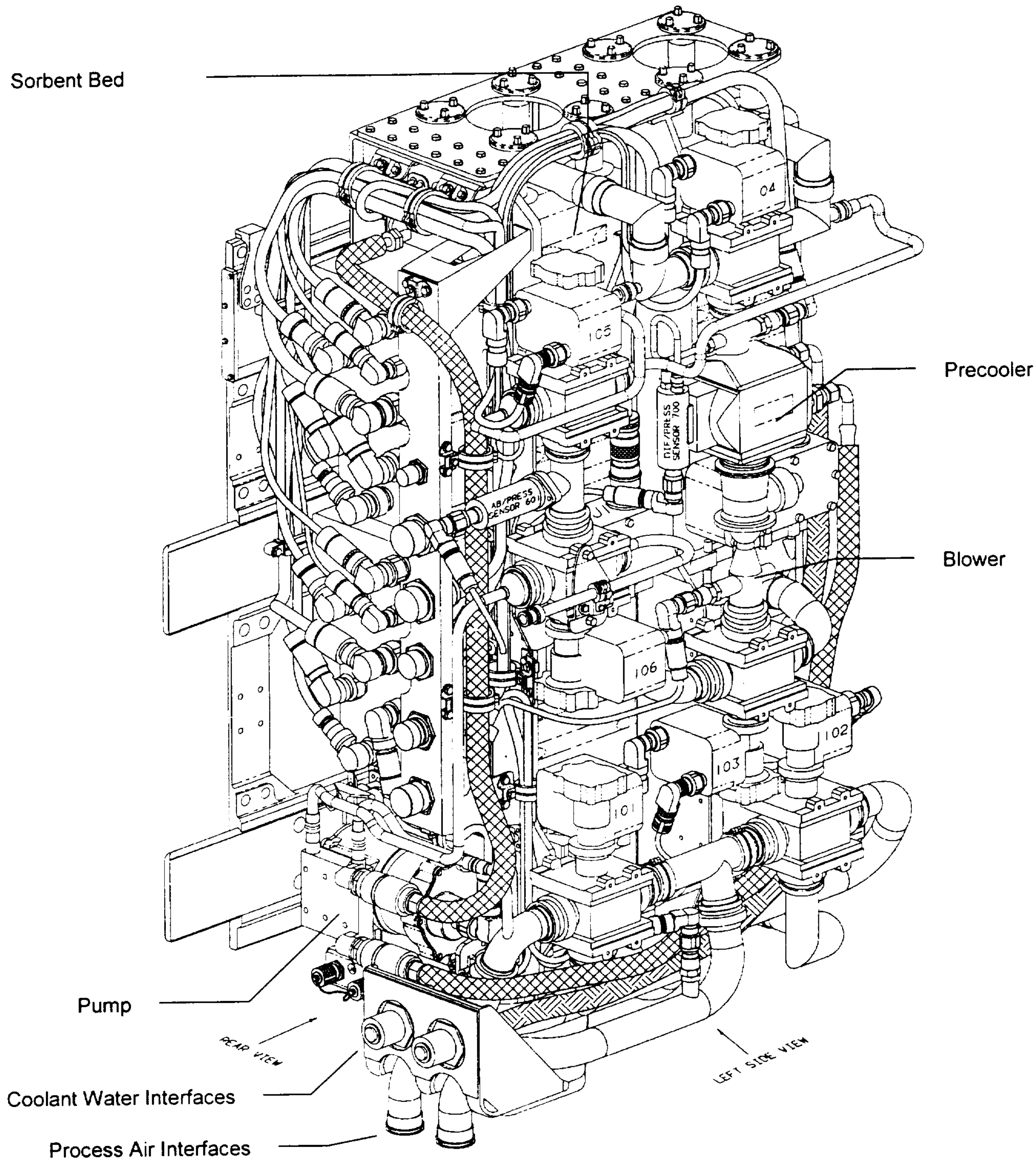

Figure 1. CDRA Flight Hardware [1]

AR SUBSYSTEM DESCRIPTION

In Figure 3, the CDRA can be seen installed into the AR rack. Other major assemblies visible are the Trace Contaminant Control Subassembly (TCCS) and the Major Constituent Analyzer (MCA). Although not reported on specifically here, both the TCCS and MCA were also operated successfully during CHE testing. The MCA was used to measure CO_2 concentration and provided data for CDRA CO_2 removal performance.

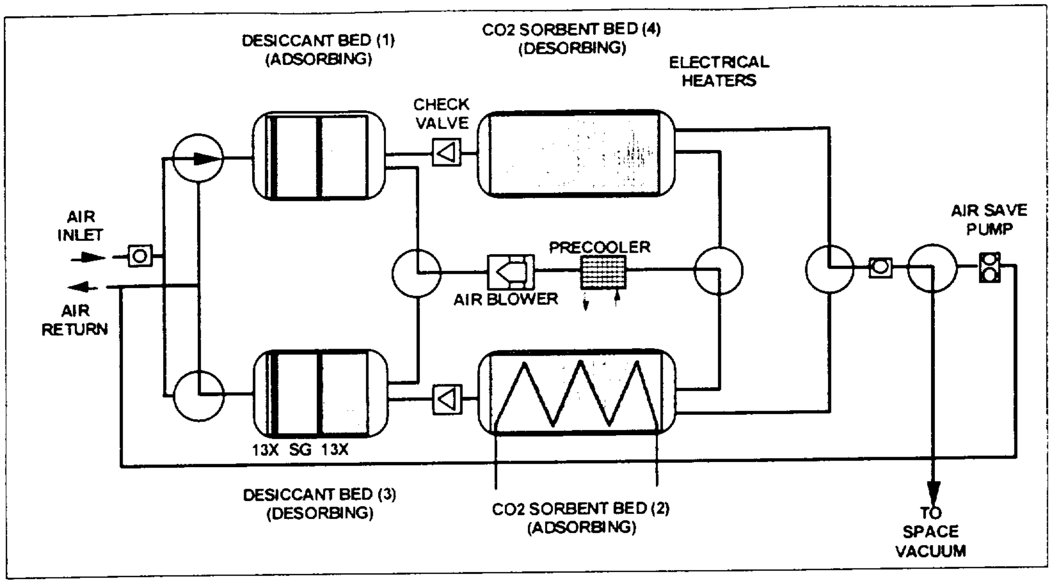

Figure 2. CDRA Schematic

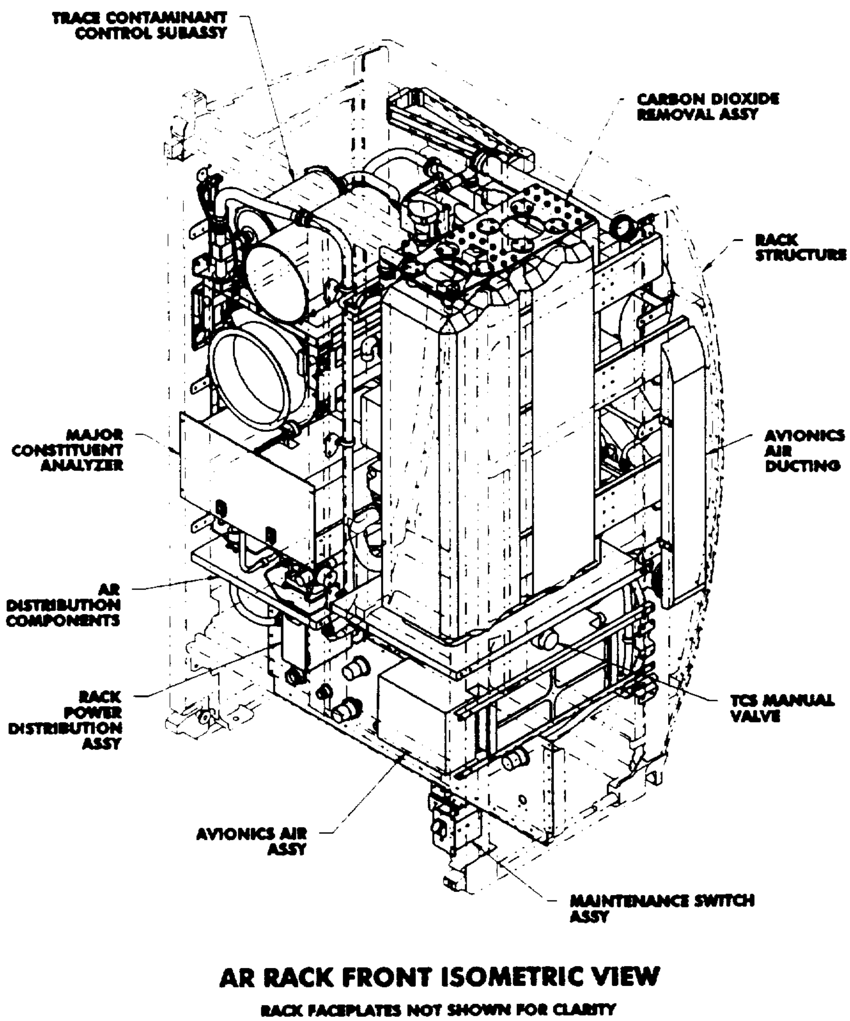

Figure 3. Atmosphere Revitalization Rack[1]

AR subsystem interfaces are shown in Figure 4. Interfaces between AR rack components are limited to Avionics Air Assembly (AAA) cooling of the MCA, sampling of the TCCS process air by the MCA, and combining the CDRA and TCCS outlet air streams (not shown). Interfaces between the AR rack and other US Laboratory interfaces are more extensive, including Lab air to the TCCS, Temperature and Humidity Control (THC) supply air to the CDRA, and Internal Thermal Control System (ITCS) cooling water to the CDRA and AAA. Selected interfaces are described in more detail below.

U.S. LABORATORY INTERFACES

AR rack location and distributed AR hardware in the U.S. Lab are shown in Figure 5. The CDRA inlet air is supplied via a dedicated line, tapping into the outlet of the common cabin air assembly (CCAA) condensing heat exchanger. This location provides cool air of low humidity, enabling higher CDRA performance. The process air line is connected to both CCAA units, only one of which is operational at one time. A process air valve selects the active CCAA.

Carbon dioxide is vented overboard via a dedicated 1.27 cm (½ inch) line. Two CO_2 vent valves (one shown, one located inside the AR rack) are closed during CDRA non-operational periods. The valves close in the case of power failure to prevent loss of atmosphere to space vacuum.

Other AR hardware items shown are the air sample lines, valves, and ports. The sample port shown supplied air to the MCA for the purpose of measuring the Lab atmosphere during CHE testing. Samples lines will be used in orbit to sample the atmosphere in other modules.

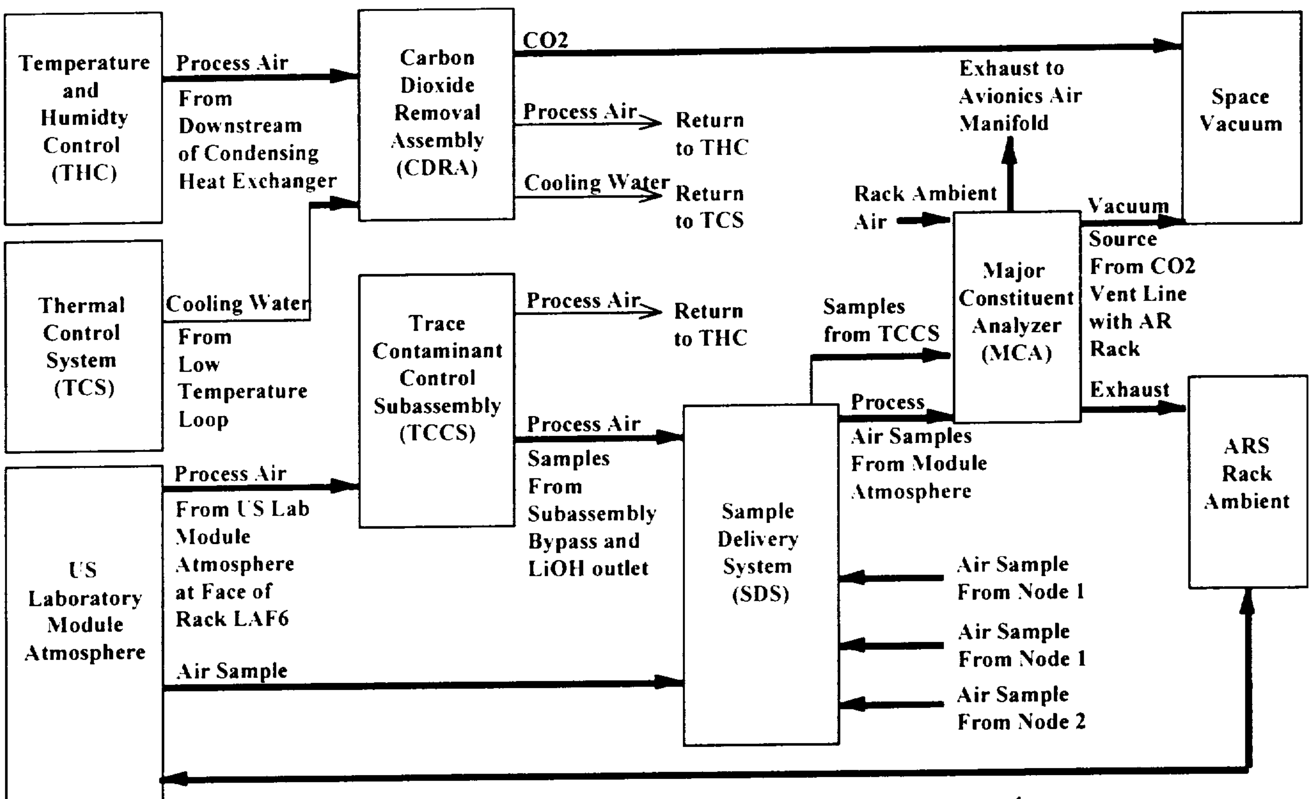

Figure 4. Atmosphere Revitalization Subsystem Rack Interfaces[1]

TEST PURPOSE

The Closed Hatch ECLSS test was conducted as a qualification test of three ECLS subsystems, including the Temperature and Humidity Control Subsystem, the Atmosphere Control and Supply (ACS) Subsystem, and the Atmosphere Revitalization Subsystem. Testing was conducted at Kennedy Space Center from April 30 through May 8, and was comprised of a series of test cases performed with a range of loading conditions and control variable setpoints.

CO_2 injection rates, humidity injection rates, and sensible heat loads were varied to simulate varying crew metabolic loads and other on-orbit variations. Oxygen removal was active only during ACS performance testing.

Internal Temperature Control Subsystem (ITCS) coolant setpoints (both moderate and low temperature loops) were varied at the limits of their specification ranges. Cabin temperature and pressure setpoints were also varied. Details of each test case can be seen in Table 1.

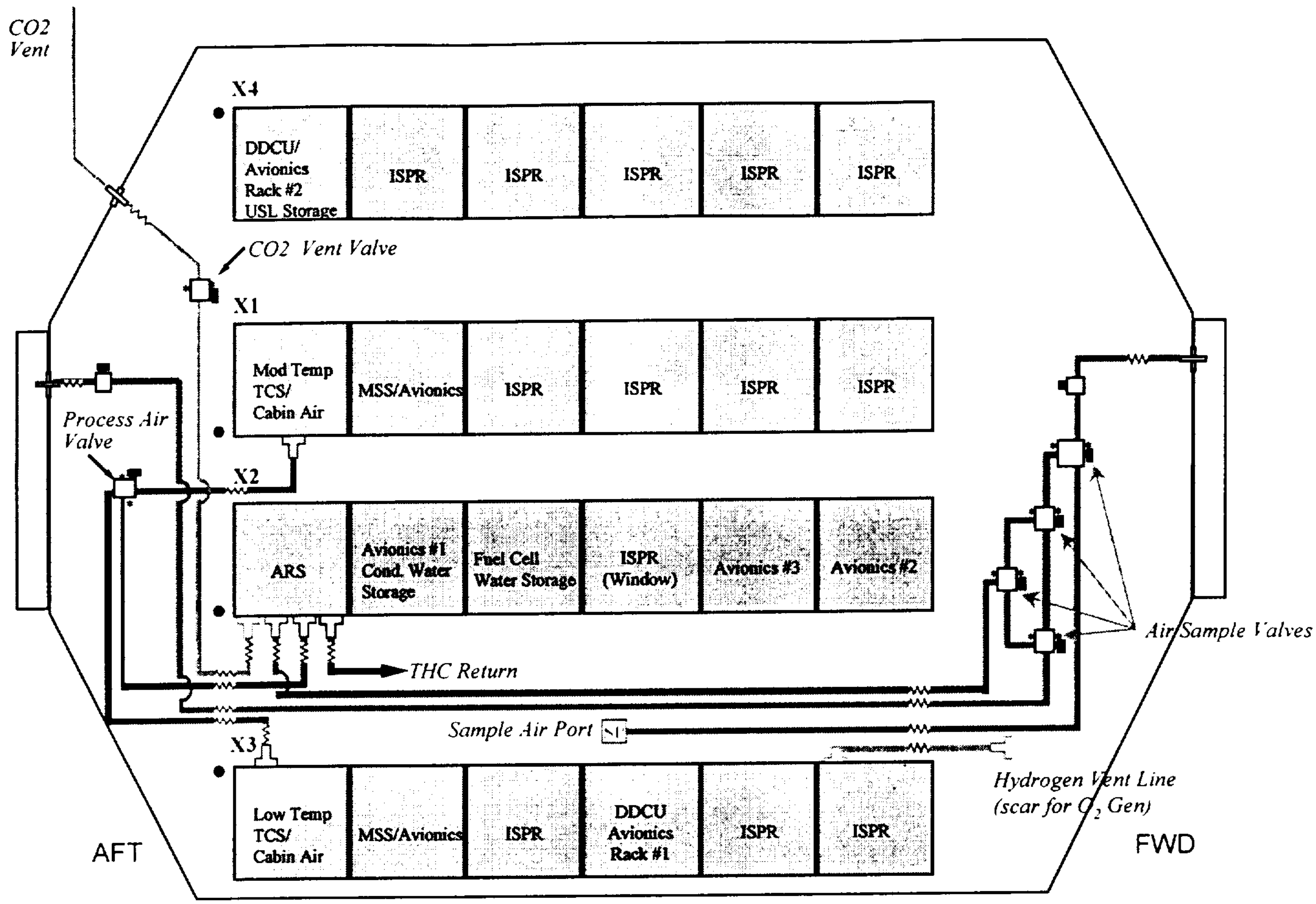

Figure 5. U.S. Laboratory Atmosphere Revitalization Schematic[2]

Table 1. Closed Hatch ECLSS Qualification Test Cases[2]

CLOSED-HATCH ECLSS QUALIFICATION TEST CASES							
	Control Variables						
	Coolant Temp Setpoints		CO_2 Load	Latent Load	Sensible Load	Cabin Temp Setpoint	Cabin Pressure Setpoint
Test Cases	LTL	MTL	lb/day	lb/day	W	°F	psia
Test Case 1, Preconditioning of Module							
Condition 1, CDRA Dryout	40 °F (+3/-2)	63 °F (±2)	13.2	12	1750 (±100)	72 (±3)	14.9
Test Case 3, CO_2 Removal Performance							
Condition 1A, High Moisture	40 °F (−3/-2)	65 °F (+0/-4)	13.2	12	2885 (+100/-0)	65(4)	14.9
Condition 1B, High CO_2 Load	43 °F (+0/-5)	61 °F (+4/-0)	13.2	12	940 (+0/-100)	65 (±3)	14.9
Condition 2, Medium CO_2 Load	43 °F (-0/-5)	61 °F (+4/-0)	8.8	12	940 (+0/-100)	65 (±3)	14.9
Condition 3, Low CO_2 Load	43 °F (+0/-5)	61 °F (+4/-0)	6.6	12	940 (+0/-100)	65 (±3)	14.9

TEST SETUP

When in orbit, the USL will obtain power from solar panels, cooling from the ISS radiators, and have access to the vacuum of space. For ground testing of the Lab, various support equipment was required to provide, for example, power, data interfaces, cooling water, a vacuum source, and simulation of crew metabolic loading. Selected interfaces are shown in Figure 6 below. Supporting equipment critical to qualification testing of the CDRA are discussed below.

METABOLIC SIMULATOR

In order to test the CO_2 removal capability of the CO_2 removal assembly, simulation of the crew metabolic CO_2 production was required. The CHE Qualification Test Readiness Review (TRR) documentation provides the following description[2]:

Simulates the principal metabolic functions of up to a six-person crew, worst-case animal and biological contributions, and total sensible heat loads.

Specific functions include:

- CO_2 introduction into the USL via a CO_2 doser and monitor.
- O_2 removal from the USL via an off-the-shelf O_2 concentrator and monitor.
- Airborne sensible heat introduction into the USL via heaters and temperature sensors.
- Humidity introduction into the USL via an ultrasonic humidifier and a dewpoint sensor.

VACUUM SYSTEM

As shown in Figure 5, the CDRA has a dedicated CO_2 vent line, which will vent to space vacuum when the USL is in orbit. An accumulator, roughing pump and turbo pump provided a simulated space vacuum for USL CHE Qualification testing. A four-inch duct was provided as input to the accumulator. Pressure measurements were taken inside the 1/2 inch CO_2 vent line and the 4 inch duct to insure that choked flow was achieved during CO_2 desorption.

TEST HATCH

In order to maintain a closed environment inside the USL and provide the required support equipment interfaces, a test hatch was designed and built. As described in the CHE Qualification Test Readiness Review[2]:

SK683-53277-1, Test Hatch, provides fluid and electrical feedthroughs for support equipment interfaces to the internal USL.

- Fluid Interfaces include:
  - ITCS supply and return hoses for FE 1247-1 top, middle, and bottom units of Carts 2 and 3
  - 7 CO_2 sample ports, 1 CO_2 return port, and 1 CO_2 insertion port
  - Oxygen Removal port (from oxygen concentrator in USL).
  - Water insertion port (to ultrasonic humidifier in USL).
  - FE 1401 nitrogen insertion port.
- Electrical Interfaces include:
  - 1 port for FE 1247-1 (Carts 2 & 3) RTDs and dP sensors.
  - 7 ports for FE 1413 auxiliary instrumentation.
- 3 ports for FE 1243:
  - Oxygen concentrator.
  - Strip heaters and ultrasonic humidifier.
  - Instrumentation

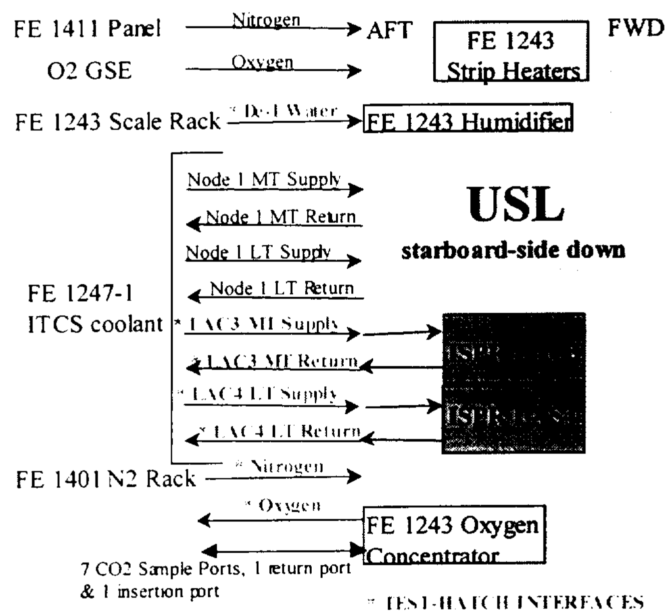

Figure 6. Supporting Equipment Interfaces[2]

TEST DUCTS

One objective of the USL CHE Qualification Test was to measure the flow rate of the CDRA integrated with the CCAA. To this end, test ducts were constructed using a modified pitot-type tube and pressure measurements to derive mass flow rate.

TEST PROCEDURE AND CONDUCT

TEST CASE 1, CONDITION 1, CDRA DRYOUT AND PROCESS AIR FLOWRATE CHECKOUT

The USL CHE Qualification Test consisted of numerous conditions, a subset of which is shown in Table 1. The first test case was to both ensure dryout of the CDRA and set CDRA process air at the desired flowrate. Dryout is performed for 24 hours with the sorbent bed heater setpoint at 204°C (400°F) as opposed to the 127°C (260°F) setpoint used for normal operating mode, otherwise known as power-save mode. Dryout was required here to insure previous AR rack standalone testing with ambient inlet air would not adversely effect CO_2 removal performance.

The initial blower speed was 115,000 RPM and provided a flowrate of 39 kg/hr (86.5 lb/hr), averaged over a full cycle or 288 minutes. Since a flow rate greater than 41 kg/hr (90 lb/hr) was required to insure adequate CO_2 removal performance, the blower speed was then increased to 120,000 RPM. For this blower speed, average flowrate over the next three cycles was 42.7 kg/hr (94.1 lb/hr), well above the minimum.

The exit process air of the TCCS at 0.9 kg/hr (2 lb/hr) joins that of the CDRA prior to dumping into the CCAA return line. To insure operation of the TCCS does not affect CDRA flowrate, the TCCS was started and the process air flowrate re-measured. The resulting value was 42.3 kg/hr (93.3 lb/hr), still well above the 90 lb/hour minimum. Note that there is a large difference in flow rate, averaging about 2.7 kg/hr (6 lb/hr), between half-cycle 1 and 2. This may to be due to the blower setting up a rotation in the flow. Resistance to flow would then depend on the position of valve 104 and thus the direction of the 90° bend. Valve 104 selects the proper sorbent bed for the current half-cycle.

TEST CASE 3, CO_2 REMOVAL PERFORMANCE

CDRA performance was measured during this test case. Results are shown in Figure 7. Two methods of CO_2 partial pressure measurement were employed. A Horiba VIA-510 Dual Beam Non-Dispersive Infrared (NDIR) analyzer was obtained for high repeatability (0.5% full scale specification). This was employed to measure both CDRA CO_2 removal performance and verify MCA accuracy. However, levels were much lower than expected (see the "Raw Horiba" trace in Figure 7). After extensive troubleshooting, it was determined that the calibration gases procured for the Horiba analyzer were incorrectly mixed. Post-test calibration of the Horiba analyzer provided a near-linear correction factor[3]. As shown, the MCA and Horiba are in close agreement following correction (see "Corrected Horiba"). CO_2 requirement levels are determined by the equation below[4]:

$$ppCO2 = (HEU + 0.7085)/1.723$$

where, HEU = metabolic CO_2 generation rate for one person (2.2 lb/dy CO_2)

$ppCO_2$ = Carbon Dioxide partial pressure in the Lab atmosphere, torr

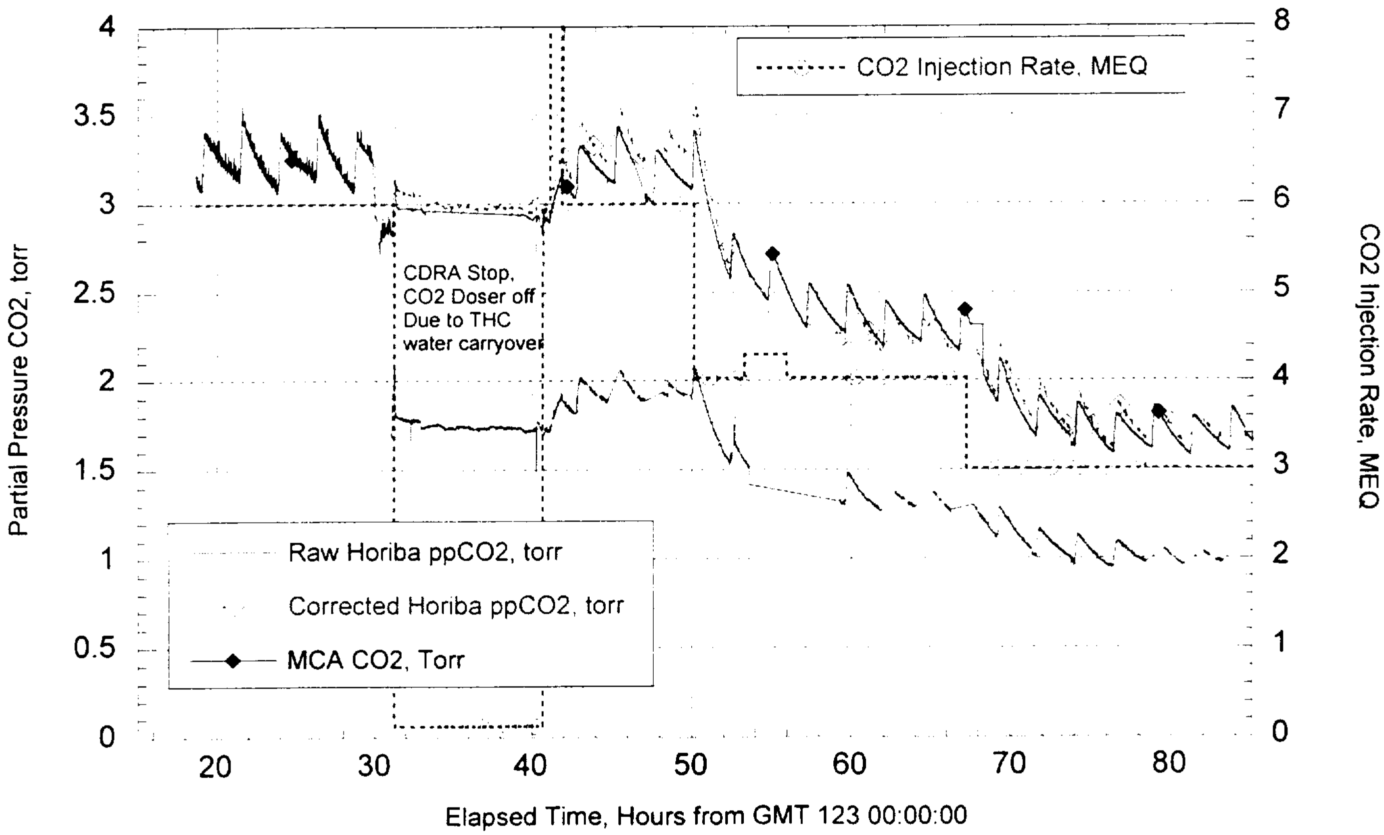

Figure 7. Cabin CO_2 Levels for Test Case 3

Test Case 3, Condition 1B, High CO_2 Load

CDRA CO2 removal performance was measured in Conditions 1B, 2, and 3, with varying CO2 injection rates. The first condition was with CO2 injection rate set at the metabolic equivalent of six crewmembers, or 6 kg/dy (13.2 lb/dy). Cabin CO2 partial pressure levels for this condition are shown in Figure 8. Sequential half-cycles are indicated by numbers in circles.

At approximately 31 hours elapsed time, the CCAA experienced a water carry-over event. The CDRA and CO2 doser were shutdown for nearly 10 hours. Following restart, CO2 injection levels were increased temporarily to restore the concentration level. Since the pre-shutdown concentration was not actually restored, half-cycles 53 through 56 were used to calculate CDRA removal performance.

Horiba data was not available for these half-cycles. This analyzer was configured to sample CDRA inlet and outlet streams as well as three cabin air locations. Gaps in the cabin Horiba data occur during for periods when valves were configured to sample alternate locations. To provide an estimate of Horiba measured concentration for half-cycles 53 to 56, values for half-cycles 59 through 60 were compared with MCA values, yielding a constant Horiba offset of 0.12 torr.

Test Case 3, Condition 2, Medium CO_2 Load

For the medium CO2 load case, the injection rate was to be equivalent to a four person loading, or 4 kg/dy (8.8 lb/hr). Actual injection rate was 8.87 lb/hr. Cabin CO2 partial pressure levels for this condition are shown in Figure 9. The MCA and Horiba values are in close agreement, and well below the requirement. A comparison of MCA and Horiba values for half-cycle 66 yields an Horiba offset of –0.03 torr. Half-cycles 67 and 68 were used to calculate CDRA removal performance. Results for this case are conservative, since steady-state cabin levels are not quite achieved.

Test Case 3, Condition 3, Low CO_2 Load

For the low CO2 load case, the injection rate was equivalent to a 3 person loading, or 3 kg/dy (6.6 lb/hr). Cabin CO2 partial pressure levels for this condition are shown in Figure 10. Once again the MCA and Horiba values are in close agreement, and well below the requirement. Half-cycles 75 through 78 were used to calculate CO2 removal performance. Comparison of MCA and Horiba values during half-cycle 72 yielded an offset of 0.03 torr.

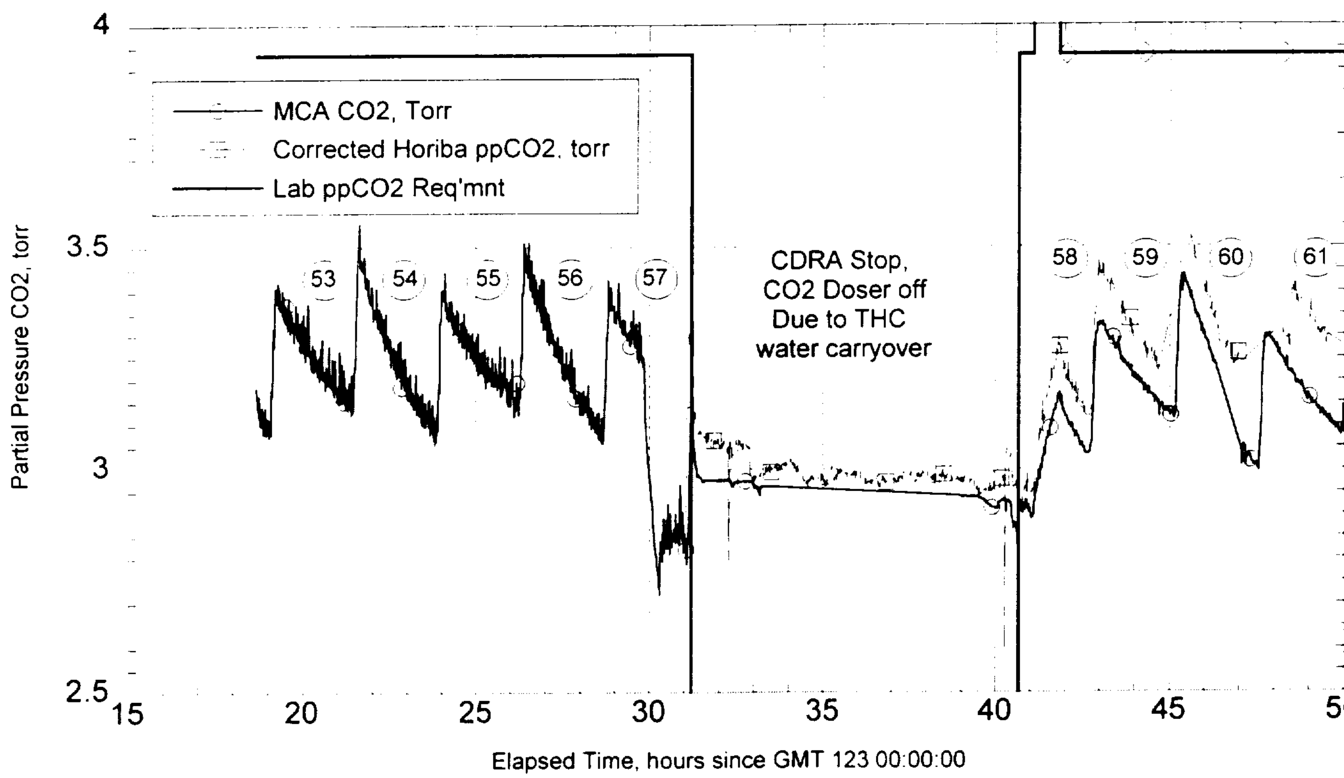

Figure 8. Cabin CO_2 Levels for High CO_2 Loading

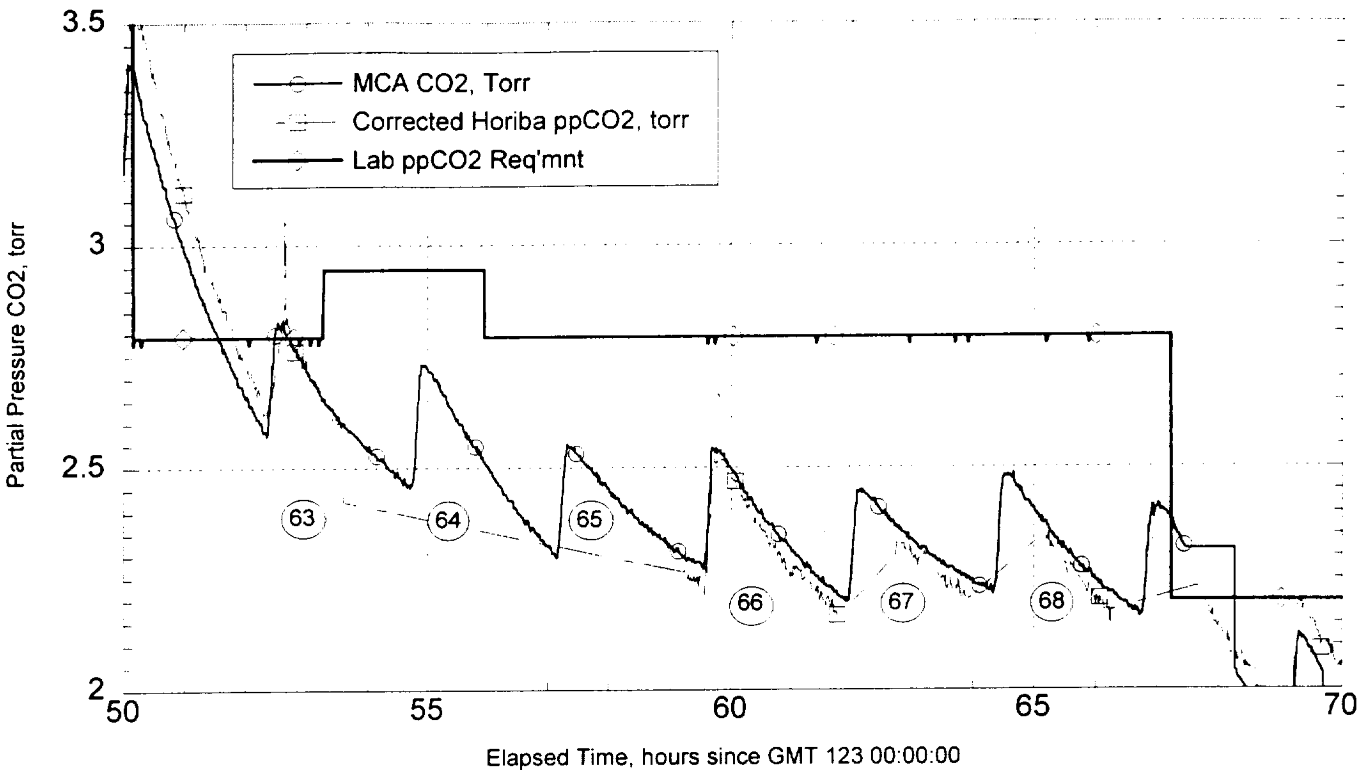

Figure 9. Cabin CO_2 Levels for Medium CO_2 Loading

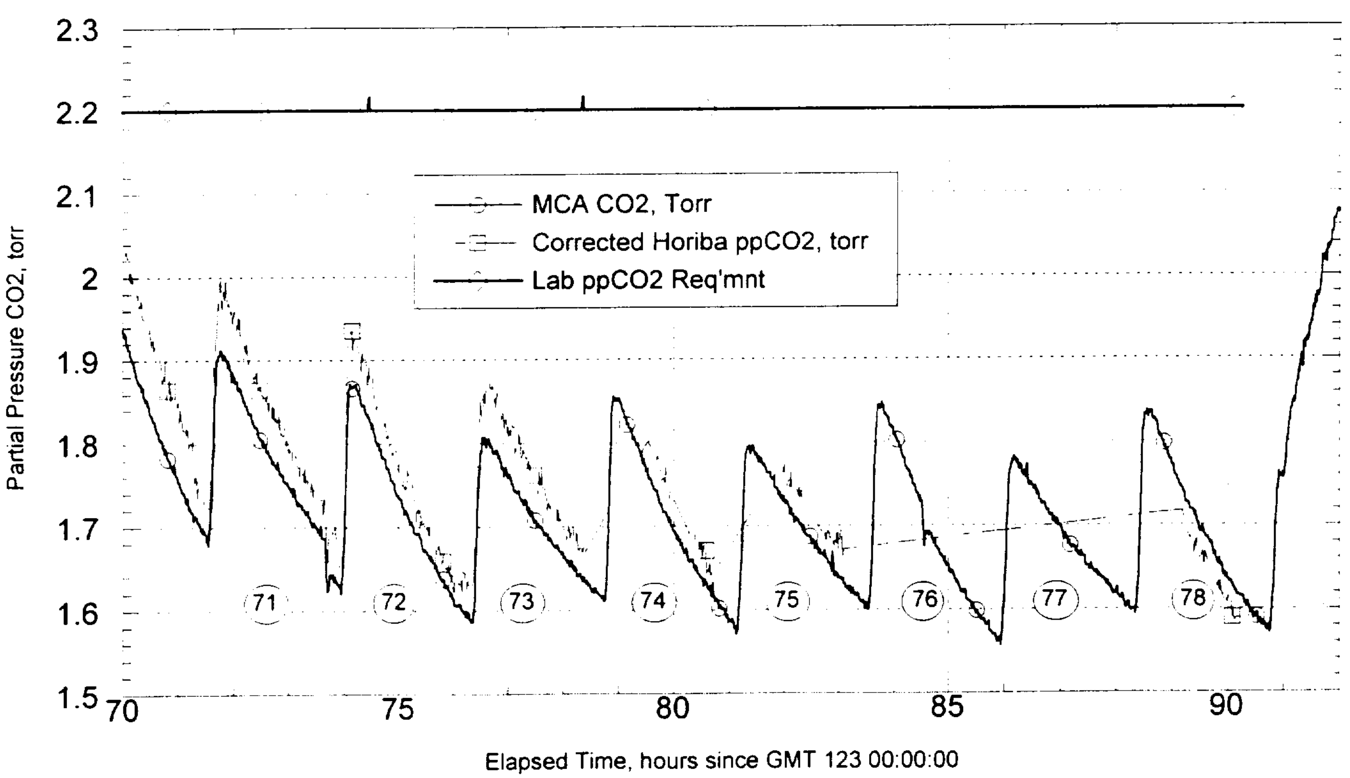

Figure 10. Cabin CO_2 Levels for Low CO_2 Loading

RESULTS

Average CO_2 partial pressure for each half-cycle used to evaluate CO_2 removal performance is shown in Table 1. Also shown, for comparison, are values from a Boeing Product Group Three analysis of the test data[5]. The primary variation in the data is in the "Required $ppCO_2$" column, due to use of different calibration curve for the CO_2 doser. A later calibration performed by Marshall Space Flight Center Calibration Facility was used for this analysis[6].

A simplistic error analysis is illustrated in Figure 11 and Figure 12. Manufacturers advertised accuracy is used to provide error bars for the data shown in Table 2. Horiba analyzer accuracy error is the most conservative at +/-1.5% of full scale. This error includes interference with coexisting gases, repeatability, normal zero and span drift, line voltage variability, and sample flow rate variation[3]. Actual accuracy is most likely higher. CO_2 Doser accuracy error is based on bias accuracy of the calibration device, or +/-0.35% of reading[7]. Observation of test data indicated minimal drift, so bias error is probably dominant. MCA accuracy error is based on the requirement of 3% of full scale[1]. Again, actual accuracy is expected to be significantly better.

Table 2. Average CO_2 Partial Pressures

Half-Cycle	MCA $ppCO_2$, torr	Horiba $ppCO_2$, torr	Required $ppCO_2$, torr	MCA $ppCO_2$[5], torr	Horiba $ppCO_2$[5], torr	Required $ppCO_2$[5], torr
Test Condition 1B (6 Crew Equivalent)						
53	3.26		3.93			
54	3.25		3.93			
55	3.25		3.93			
56	3.24		3.93			
53-56	3.25	3.35	3.93	3.285	3.385	3.843
59-60	3.22	3.34	3.93			
Test Condition 2 (4 Crew Equivalent)						
66	2.34	2.37	2.79			
67	2.32		2.79			
68	2.31		2.79			
67-68	2.32	2.29	2.79	2.285	2.305	2.724
Test Condition 3 (3 Crew Equivalent)						
72	1.72	1.75	2.2			
73	1.72		2.2			
74	1.70		2.2			
75	1.69		2.2			
74-75	1.70	1.73	2.2	1.71	1.74	2.152
76	1.69		2.2			
77	1.68		2.2			
78	1.69		2.2			
75-78	1.688	1.718	2.2			

As shown in Figure 11, CO_2 removal performance meets requirements for worst case sensor accuracy, even with conservatism for the Horiba analyzer accuracy. Values from the Boeing Analysis[5] are shown as single points for comparison.

Using MCA analyzer values also results in CO_2 removal performance meeting requirements for worst case sensor accuracy, even with conservatism for the MCA analyzer accuracy. Figure 12 shows a near overlap of sensor error bars occurs at Condition 2. For this condition, CO_2 levels had not steadied out prior to changing the CO_2 doser value for the next test, such that CO_2 concentration was higher than its steady-state value.

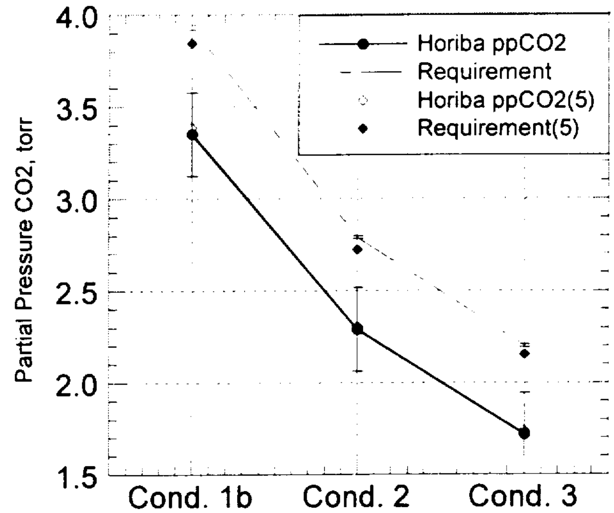

Figure 11. Error Analysis for Horiba Analyzer

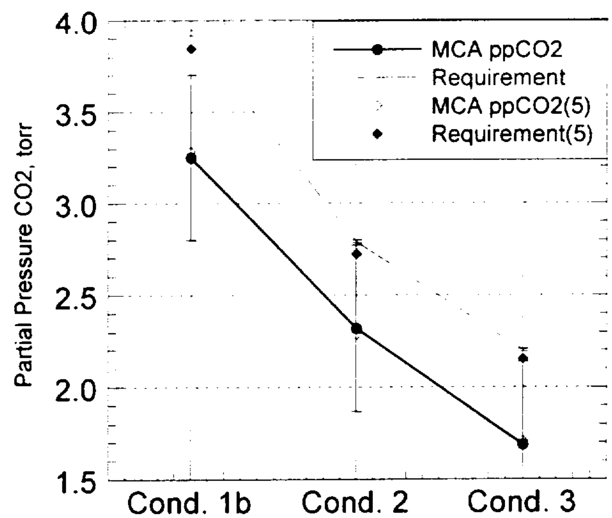

Figure 12. Error Analysis for MCA

CONCLUSIONS

With regards to the CDRA operation and performance, the Closed Hatch ECLSS Qualification test was highly successful. Operation of the CDRA was without software or hardware error, due in no small part to extensive prior regression testing at the AR rack level. CO_2 removal performance exceeded specifications for all three loading conditions, even with a conservative error analysis for the CO_2 analyzers. The information obtained during this test provides valuable model correlation and reference data.

CONTACT

James C. Knox
Mail Stop FD21
Marshall Space Flight Center
Huntsville, AL 35812
Telephone: (256) 544-4887
E-mail: James.C.Knox@msfc.nasa.gov

REFERENCES

1. Environmental Control and Life Support (ECLS) Architecture Description Document, Volume 2, Book 2, Revision C, D684-10508-02-02, Boeing Defense and Space Group, Houston, 1999

2. Sanders, Catherine, Test Readiness Review for USL Closed-Hatch ECLSS Test, Presented at the for USL Closed-Hatch ECLSS Test Readiness Review, Kennedy Space Flight Center, April 1999

3. Curtis, Robert, Post-Closed Hatch ECLSS CO2 Performance Analyses – Interim Report, Boeing Defense and Space Group, Huntsville Alabama, 1999

4. Prime Item Development Specification for United States Laboratory, International Space Station, S683-29523J, Boeing Defense and Space Group, Huntsville Alabama, November 1997

5. Russell, Madison, Flight Article Closed Hatch CO2 Removal Test, 2-8265-MRR-01-00, Boeing Defense and Space Group, Huntsville Alabama, January 2000

6. MSFC Calibration Report on ECN M634722, Marshall Space Flight Center, Alabama, June 1999

7. Conversation with Bryan Pendegraft, MSFC Calibration Facility, May 9, 2000